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Centennial-scale climate variability during the past 2000 years on the central Tibetan Plateau

Xiumei Li,1,2 Jie Liang,1,2 Juzhi Hou1,3 and Wenjing Zhang1

Abstract
It is currently suggested that climate change on the northeastern Tibetan Plateau (TP) was influenced alternately by the monsoon and the Westerlies. However, the mechanisms driving Holocene climate change on the TP remain unclear, since the extent of the influence of individual atmospheric circulation systems has not yet been clearly defined because of the shortage of high-quality paleoclimatic records. This is especially true in the central TP, where only a few ice core and paleolimnological records are available. Here, we present a decadal-resolution temperature record from Dagze Co in the central TP for the past 2000 years, based on the unsaturation index of long-chain alkenones, using an updated temperature calibration, and a record of precipitation isotopes from compound-specific isotope ratios of leaf waxes. The centennial-scale variation of the temperature and precipitation isotope records captures well-known climatic events over the past 1000 years, for example, the ‘Little Ice Age’, which was cooler and drier than the ‘Medieval Warm Period’. However, the relationship between temperature and the precipitation isotope records differed during the interval at 2000–1000 cal. yr BP compared to the past 1000 years, probably because of changes in precipitation seasonality and the additional influence of the Westerlies on the central TP. In addition, the temperature records exhibit a prominent 210-year cyclicity, suggesting a possible influence of solar radiation on temperature variability.

Keywords
alkenones, Dagze Co, late Holocene, leaf waxes, precipitation isotopes, temperature, Tibetan Plateau

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Introduction
Numerous paleoclimate records are available from the Tibetan Plateau (TP), including stable isotope records from high-elevation ice cores (Thompson et al., 1997, 2006; Yao et al., 2006) and speleothems (Cai et al., 2010) and various paleolimnological records from widespread lakes (Gasse et al., 1991, 1996; He et al., 2013a; Henderson and Holmes, 2009; Henderson et al., 2010; Herrmann et al., 2009; Kramer et al., 2010; Liu et al., 2006; Mischke and Zhang, 2010; Zhao et al., 2013; Zhu et al., 2008). However, the mechanisms driving Holocene climate change on the TP remain unclear, due to the following reasons: (1) The fact that the TP is influenced by several atmospheric circulation systems, including the Indian summer monsoon, the Asian winter monsoon, and the Westerlies, which exert significantly different climatic effects on the TP (Chen et al., 2008). Moreover, as the summer monsoon weakened and gradually retreated during the middle to late Holocene (An et al., 2000; Dykoski et al., 2005; Yuan et al., 2004), the convergence zone between the monsoon and the Westerlies would have shifted correspondingly. However, it is unclear where and when the convergence zone was located on the TP during the Holocene, which further complicates the interpretation of current paleoclimatic records from the region. (2) Among the various proxy archives from the TP, only speleothems provide precise chronological control. Both ice cores and lake sediment cores suffer from large chronological uncertainties, and in particular, the role of the reservoir effect in radiocarbon dating of lake sediment cores makes the synthesis of paleolimnological records from different sites difficult (Hou et al., 2012; Mischke et al., 2013). (3) Individual proxy indicators may respond to different climatic parameters; for example, the widely used precipitation isotope records may be influenced by temperature in the Westerly dominated regions and by precipitation amount in the monsoonal regions (Yao et al., 2013). Interpretation of isotope records is especially difficult in the central TP, which is located within the conjunction of three climate systems. Therefore, independent records of temperature and precipitation isotopes from a single climatic archive are extremely important for assessing the implications of the isotope records and for understanding the mechanisms of past climatic changes on the TP.

In this study, we first updated the calibration between the alkenone unsaturation index, \(^{14}C\), and mean annual temperature of Chu et al. (2005) by adding data from surface sediments from lakes on the TP. Subsequently, we used the updated calibration function to reconstruct temperature changes at Dagze Co, a meromictic lake in the central TP, over the last 2000 years. We
also reconstructed precipitation isotope records by measuring leaf wax hydrogen isotope ratios. The overall aim of this study was to investigate the influence of the monsoon and the Westerlies in the central TP over the past 2000 years.

Materials and methods

Study sites and samples

Dagze Co (31°49′–31°59′N, 87°25′–87°39′E; 4450 m a.s.l.) is a meromictic, carbonate-rich brackish lake in the central TP, 30 km east of the town of Nyima (Figure 1a; Wang et al., 2014). The lake is mainly fed by precipitation and by the River Bogcarg Zangbo (Figure 1b). The lake has a maximum depth of 38 m, an area of 245 km², and a watershed area of 10,885 km² (Figure 1c). According to the measurements at the Xainza Meteorological Station (~150 km southeast of the lake, mean annual precipitation is 316 mm, of which ~90% occurs in June–September. Mean annual air temperature is 0.55°C, and mean summer temperature (June–August) is 8°C. A survey of the lake in 2012 indicated that the salinity of the surface lake water was 14.69 g/L, increasing to 21.41 g/L at the bottom, with the halocline at 25–29 m. A Secchi-disk reading was 6 m. Multiple paleo-shorelines to the east of the lake suggest dramatic hydrological changes in the past (Qiao et al., 2010). Sediment core DZC2011-1 (291 cm long) was retrieved from a water depth of 37 m using a piston corer (Figure 1c). The core was subsampled continuously at an interval of 0.5 cm, and all of the samples were stored in a freezer prior to laboratory analysis.

Analytical methods

Total lipids were extracted from the lake sediments using ultrasonication and were further fractionated using flash column chromatography. About 5 g of sediment was used for extraction with dichloromethane and methanol (volume ratio = 2:1; three cycles of 15 min were used). Total lipid extracts were fractionated into neutral and acid fractions with LC-NH₂ silica gel chromatography, eluted with dichloromethane:isopropanol = 2:1 (v:v) and ether:acetic acid = 96:4 (v:v), respectively. The neutral fraction was further fractionated into three fractions using a silica gel flash column by eluting hexane, dichloromethane, and methanol. The dichloromethane fraction was saponified with 1 N KOH in a methanol solution (with 5% water) at 75°C overnight to remove alkenoates and was then used to measure long-chain alkenones. The acid fraction was methylated using anhydrous 2% HCl in methanol. Hydroxyl acids were removed using silica gel column chromatography (with dichloromethane as a solvent) to avoid chromatographic coelution.

Quantification and identification were carried out using gas chromatography (GC) and gas chromatography–mass spectrometry (GC-MS). An HP 6890 chromatograph interfaced to a Finnigan Delta+ XL stable isotope mass spectrometer through a high-temperature pyrolysis reactor was used for hydrogen isotope analysis. The H³⁺ factor was determined daily prior to sample analysis (the average value was 2.0 during the course of the study). The precision (1σ) of triplicate analyses was <±0.002. The accuracy was routinely checked by inclusion of laboratory isotope standards every six measurements. The δD values obtained for individual acids (as methyl esters) were corrected by mathematically removing the isotopic contributions from the added group. The δD value of the added methyl group was determined by acidifying and then methylating (together with the samples) the disodium salt of succinic acid with a predetermined δD value (Huang et al., 2002).

Chronology

Age control for core DZC2011-1 was obtained using a combination of ²¹⁰Pb and ¹³⁷Cs dating of the uppermost sediments (0–11 cm; Figure 2a–c) and AMS-¹⁴C dating of the sediments below 20 cm depth (Table 1; Figure 2d). Seven ¹⁴C dates were obtained and were calibrated using CALIB 7.0.2 (Table 1). Both the ¹⁴C ages and calibrated ages exhibit a robust linear trend with their corresponding depths in the sediment core (Figure 2d). Linear regression of the calibrated ¹⁴C ages yielded an age of 2586 years for the depth of 0 cm (Figure 2d), which can be regarded as the average reservoir age for the sediment core. We
Figure 2. Age controls for Dagze Co sediment core DZC2011-1. (a) $^{210}$Pb measurements for the uppermost 11 cm. (b) $^{137}$Cs measurement for the uppermost 11 cm. (c) Chronology for the upper 11 cm of sediment core DZC2011-1 based on $^{210}$Pb and $^{137}$Cs dating. (d) Calibrated original $^{14}$C ages (open circles). Linear regression of the calibrated original ages resulted in an age of 2586 years at 0 cm. A reservoir age of 2552 years (see text) was subtracted from the original calibrated $^{14}$C ages (solid circles), which were used to construct the final chronology for DZC2011-1. (e) Age–depth model for core DZC2011-1 (gray) using the ‘Bacon’ program (Blaauw and Christen, 2011), with an overlay of the calibrated distributions of the individual dates (black). Gray dots indicate the model’s 95% probability intervals.

Table 1. Radiocarbon ages and calibrated ages using CALIB7.0.2 for DZC2011-1.

<table>
<thead>
<tr>
<th>Laboratory code</th>
<th>Depth (cm)</th>
<th>$^{14}$C age (yr BP)</th>
<th>$^{14}$C error (years)</th>
<th>Calibrated age (yr BP) $^{2}$σ error</th>
<th>Cal age (RA corrected)$^{a}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta317161</td>
<td>20</td>
<td>2700</td>
<td>20</td>
<td>2803</td>
<td>43</td>
</tr>
<tr>
<td>BA130012</td>
<td>30</td>
<td>3030</td>
<td>30</td>
<td>3213</td>
<td>38</td>
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<tr>
<td>BA120309</td>
<td>100</td>
<td>3230</td>
<td>30</td>
<td>3446</td>
<td>65</td>
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<tr>
<td>BA120312</td>
<td>150</td>
<td>3680</td>
<td>30</td>
<td>4002</td>
<td>89</td>
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<tr>
<td>BA120310</td>
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<td>4020</td>
<td>30</td>
<td>4478</td>
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<td>4849</td>
<td>19</td>
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<tr>
<td>BA120311</td>
<td>289</td>
<td>4895</td>
<td>30</td>
<td>5625</td>
<td>38</td>
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</tbody>
</table>

$^{a}$Cal ages (RA corrected) represent the calibrated ages subtracting reservoir ages (2552 cal. yr). Cal ages are used to construct chronological controls at DZC2011.
also extrapolated the 210Pb-based age–depth relationship to 20 cm depth (the location of the uppermost 14C date) and obtained an age difference between the 210Pb date and the calibrated 14C age of 2517 years, and this can be considered to be the reservoir age at that depth. The two independent reservoir ages were averaged (2552 cal. yr) and then subtracted from the original calibrated ages. Unfortunately, any past changes in the reservoir age are unknown. The final step was to use the Bacon program (Blaauw and Christen, 2011) to construct the final chronology for the sediment core (Figure 2e).

Spectral analysis
Spectral analysis was performed on the temperature records at Dagze Co using REDFIT (version 3.8; Schulz and Mudelsee, 2002). REDFIT estimates red-noise spectra directly from unevenly spaced time series, without requiring interpolation. We performed spectral analysis using REDFIT with the following parameters: nsim (number of Monte Carlo simulations) = 1000, ofac (oversampling factor for Lomb–Scargle Fourier transform) = 4.0, hifac (maximum frequency to analyze) = 1.0, and iwin = 1 (i.e. a Welch window was used to suppress side lobes).

Table 2. Lakes in the Tibetan Plateau used to update the relationship between $U'_{37}$ and mean annual temperature.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Longitude (°)</th>
<th>Latitude (°)</th>
<th>Elevation (m)</th>
<th>$U'_{37}$</th>
<th>MAAT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bieruoze Co</td>
<td>82.93°E</td>
<td>32.43°N</td>
<td>4407</td>
<td>0.210</td>
<td>3.0</td>
</tr>
<tr>
<td>Darebu Co</td>
<td>83.22°E</td>
<td>32.47°N</td>
<td>4436</td>
<td>0.319</td>
<td>5.5</td>
</tr>
<tr>
<td>Dagze Co</td>
<td>87.55°E</td>
<td>31.89°N</td>
<td>4450</td>
<td>0.348</td>
<td>6.1</td>
</tr>
<tr>
<td>Nam Co</td>
<td>90.66°E</td>
<td>30.72°N</td>
<td>4729</td>
<td>0.101</td>
<td>2.0</td>
</tr>
<tr>
<td>Rebang Co</td>
<td>80.60°E</td>
<td>33.03°N</td>
<td>4326</td>
<td>0.185</td>
<td>1.7</td>
</tr>
<tr>
<td>Selin Co</td>
<td>89.05°E</td>
<td>31.78°N</td>
<td>4544</td>
<td>0.178</td>
<td>0.4</td>
</tr>
<tr>
<td>Qige Co</td>
<td>85.53°E</td>
<td>31.20°N</td>
<td>4667</td>
<td>0.192</td>
<td>1.3</td>
</tr>
<tr>
<td>Zigetang Co</td>
<td>90.85°E</td>
<td>32.06°N</td>
<td>4573</td>
<td>0.267</td>
<td>4.5</td>
</tr>
<tr>
<td>Chabyer Caka</td>
<td>84.05°E</td>
<td>31.44°N</td>
<td>4429</td>
<td>0.103</td>
<td>1.1</td>
</tr>
<tr>
<td>Gongzhu Co</td>
<td>82.13°E</td>
<td>30.64°N</td>
<td>4789</td>
<td>0.141</td>
<td>3.5</td>
</tr>
</tbody>
</table>

MAAT: mean annual air temperature.

Results
Relationship between $U'_{37}$ and mean annual temperature
Because the original calibration between $U'_{37}$ ($U'_{37} = [C37:2]/([C37:2]+[C37:3])$) and mean annual temperature in Chu et al. (2005) only includes two lakes from the TP (the other lakes are from low-elevation regions), we updated the calibration by adding additional data from lake surface sediments collected from the TP in order to improve its coverage of high-altitude regions. We collected surface sediment samples at 25 lakes from the TP in 2012 and detected unsaturated alkenones in 10 lakes (Table 2). Mean annual air temperatures from 1991 to 2012 (the approximate ages of surface sediment at 0–1 cm based on 210Pb dating) at the lakes were estimated from Chen et al. (2011). The relationship between $U'_ {37}$ and mean annual temperature for the 10 Tibetan lakes is $U'_ {37} = 0.0353 * T + 0.1022$ ($r^2 = 0.6613$, $n = 10$, $p < 0.01$). The slope is very close to that of the calibration ($U'_ {37} = 0.0374 * T + 0.0983$) in Chu et al. (2005). After adding the data from 10 Tibetan lakes, the updated calibration equation is $U'_ {37} = 0.03733 * T + 0.09799$ ($r^2 = 0.8460$, $n = 47$, $p < 0.01$); residual mean square is 0.005873, corresponding to 1.5°C (Figure 3). The addition of the new Tibetan lake surface sediment data does not significantly improve the correlation between $U'_ {37}$ and mean annual temperature; however, it does increase our confidence in the application of the calibration to lakes in the TP.

Temperature variability in the past 2000 years
We measured only concentrations of unsaturated alkenones and calculated $U'_ {37}$ values for the sediments above 200 cm depth, since the concentration of alkenones of the deeper sediments was below detection. The $U'_ {37}$ values were converted to mean annual air temperature using the updated calibration (Figures 3 and 4). The $U'_ {37}$-based temperature for the uppermost sample at Dagze Co (0–1 cm, ~2002 AD based on 210Pb dates) is 6.5°C, close to the mean summer temperature from 1981 to 2012 at Xainza Meteorological Station. The temperature record fluctuates significantly...
over the past 2000 years, with relatively cool intervals at 300–500, 750–950, ~1100, and 1400–1550 cal. yr BP (Figures 4 and 5). The lowest temperature occurred at ~1700 cal. yr BP. The cool interval from 300 to 500 cal. yr BP, when the temperature was ~3°C lower than present, is correlative with the ‘Little Ice Age’ (LIA). The ‘Medieval Warm Period’ (MWP) occurred between 500 and 750 cal. yr BP, when the temperature was similar to the modern temperature. The modern temperature is lower than the average temperature during the warm intervals between 2000 and 1000 cal. yr BP. In addition, the Dagze Co temperature record exhibits strong cyclical variability, and spectral analysis reveals a prominent 210-year cycle (>95% confidence interval; Figure 6).

Precipitation isotope variations over the past 2000 years

We measured hydrogen isotope ratios (δD) of three long-chain n-alkanoic acids, including C26, C28, and C30 n-acids. Since woody plants and herbaceous plants differ significantly in their leaf wax δD values (Hou et al., 2007; Sachse et al., 2012), we calculated weighted average δD values for C26 and C28 n-acids (Figure 4) in order to minimize the bias in isotope ratios between woody and herbaceous plants. The concentration of C30 n-acids is too low in most of the samples and is, therefore, excluded from the calculation. The hydrogen isotope records at Dagze Co exhibit significant variability over the past 2000 years (Figure 3). Relatively enriched δD values occurred at 200–400, 750–900, 1100–1400, and 1600–1800 cal. yr BP, and depleted δD values occurred at 400–750, ~950, and 1400–1600 cal. yr BP. During the past 1000 years, higher δD values occurred in cool periods such as the LIA, and at ~950 cal. yr BP when the temperature was ~3°C lower than during the preindustrial period. Lower δD values occurred in warm periods such as the MWP, and at ~950 cal. yr BP. However, between 2000 and 1000 cal. yr BP, lower δD values coincided with relatively cooler periods, such as the cool intervals at ~1100 cal. yr BP, and between 1400 and 1550 cal. yr BP.

Discussion

Factors influencing precipitation isotopes in the central TP

Hydrogen isotope ratios of sedimentary leaf waxes have been demonstrated to reflect changes in precipitation isotope composition (δD) on a global basis (Garcin et al., 2012; Günther et al., 2013; Hou et al., 2008; Rao et al., 2009; Schefuß et al., 2005). Complex hydrogen isotopic fractionation occurs between the production of leaf waxes and their preservation in sediments (Sachse et al., 2012). The strong aridity in the central TP may significantly alter the leaf wax hydrogen isotope ratios. Nevertheless, surveys of modern lake surface sediments and plants (Günther et al., 2013), and comparison of leaf wax δD records with ice core isotope records in the TP (Günther et al., 2011), suggest that the sedimentary leaf wax δD may document past changes in precipitation isotope ratios. Therefore, the leaf wax δD variations at Dagze Co potentially reflect past changes in precipitation isotopes in the central TP.

Investigations of modern precipitation isotopes suggest that in the south and eastern TP, which is mainly influenced by the monsoon, the δD variation reflects changes in precipitation amount. In contrast, in the north and western TP, which is influenced by the Westerlies, the δD variation is mainly affected by temperature (Gao et al., 2011; Tian et al., 2007; Yao et al., 2013). Precipitation at Dagze Co originates from the Indian Ocean, based on observations at Xainza Meteorological Station and the results of HYSPLIT.
The δP record at Dagze Co differs from the moisture influenced by the same climatic regime. The monsoon influence core from the central TP (Thompson et al.) indicates that the summer precipitation is mainly supplied to the central TP by air masses originating in the Indian Ocean. Therefore, we infer that variations in precipitation hydrogen isotope ratios at Dagze Co mainly reflect changes in the intensity of the Indian summer monsoon. However, the effect of temperature on the precipitation isotope ratios cannot be excluded for times when the monsoon weakened and the Westerlies intensified.

**Monsoon influence on the central TP in the past 1000 years**

The temperature and δD records at Dagze Co indicate that during the past 1000 years, the climate was cool and dry during the LIA and warm and humid during the MWP (Figure 4). A similar trend has been observed in monsoonal regions such as Wanxiang Cave in western China (Zhang et al., 2008) and in the Puruogangri ice core from the central TP (Thompson et al., 2006), suggesting that over the past 1000 years, the central TP and northeastern TP were influenced by the same climatic regime. The monsoon influence in the TP during the past 1000 years has also been observed in numerous paleolimnological records (He et al., 2013a; Henderson and Holmes, 2009; Henderson et al., 2010) and tree ring records (Yang et al., 2003, 2009) from the northeastern TP, implying that over the past 1000 years, the Indian monsoon prevailed in the TP. However, the δP record at Dagze Co differs from the moisture records from Lake Sugan and Lake Gahai in the Qaidam Basin, northern TP (He et al., 2013b). The temperature records from Lakes Sugan and Gahai document a relatively warm MWP, while moisture records derived from the percentage of tetra-unsaturated alkenones (37.4%) indicate a relatively dry environment in the Qaidam Basin, probably suggesting differences in moisture source between the two areas. Nevertheless, variations in the titanium concentration of sediments from the Cariaco Basin (Haug et al., 2001) reveal that the inter-tropical convergence zone (ITCZ) shifted northwards during the MWP and then shifted southwards during the LIA, suggesting that climate variability in the central TP is closely related to shifts in the ITCZ location.

**Climate change in the central TP from 2000 to 1000 cal. yr BP**

Between 2000 and 1000 cal. yr BP, the ITCZ moved northwards, as revealed by the record of Ti concentration in the Cariaco Basin (Haug et al., 2001); and the Indian monsoon intensity was relatively strong, as revealed by speleothem δ18O records at Wanxiang Cave (Zhang et al., 2008). However, the hydrogen isotope records at Dagze Co were relatively enriched. The temperature records exhibit a more fluctuating pattern of variation that is similar to that of the total solar irradiance record (Figure 5). Scrutiny of the temperature and isotope records at Dagze Co indicates that lower δD values coincided with cool intervals such as at ~1100 and 1400–1550 cal. yr BP, while higher δD values coincided with warm intervals such as 1100–1250 and 1550–1700 cal. yr BP (Figure 5). This contrasts with our observation that over the past 1000 years, higher δD values occurred during cool periods. The temperature and precipitation isotope records from Dagze Co indicate that at around 1000 cal. yr BP, the climate in the central TP changed significantly. Between 2000 and 1000 cal. yr BP, temperature variability followed changes in total solar irradiance, while the precipitation isotope ratios were affected by monsoon intensity as well as by other factors.

The relatively depleted precipitation isotope ratios during the cool intervals between 2000 and 1000 cal. yr BP may have resulted from the increased influence of the Westerlies in the central TP. During cool periods, the Indian summer monsoon would have weakened, resulting in reduced precipitation in the central TP. When the monsoon weakened, the Westerlies could have been able to penetrate into the region (An et al., 2012; Henderson et al., 2010), supplying precipitation. The moisture carried by the Westerlies would have lowered the precipitation isotope ratios, as discussed in Yao et al. (2013). Another possible factor causing the δD depletion of precipitation is the seasonality of precipitation in the central TP. As the monsoon weakened during the cool intervals, the precipitation may have occurred during a shorter time interval during the year, and this would also have contributed to the observed isotopic depletion of precipitation.

In summary, the temperature and precipitation isotope records at Dagze Co between 2000 and 1000 cal. yr BP suggest that the climate in the central TP was mainly influenced by the Indian monsoon during warm intervals but that the Westerlies may have penetrated into the region during cool intervals when the monsoon weakened.

**Cyclicity of temperature changes in the past 2000 years**

Spectral analysis of the temperature record at Dagze Co reveals a prominent peak centered at 210 years (Figure 6). The spectra are confirmed by Gaussian band pass filtering of both the temperature and solar irradiance records (Steinhilber et al., 2012). The 210-year spectral peak is well documented in the atmospheric 14C production and 10Be records, which are proxies for solar variability (Damon and Sonett, 1991). This suggests a higher sensitivity of the regional climate to solar variability during the past 2000 years. The central TP temperature increased during periods of strong solar activity, as indicated by the total solar irradiance record (Figure 5). Overall, our results suggest that during the last 2000 years, there may have been a close relationship between the central TP centennial-scale temperature variability and solar activity.

The mechanisms involved in a relatively small amplitude change in solar irradiation resulting in a disproportionately large climatic response in the northern hemisphere continents have been discussed previously (Bard et al., 2000; Lean and Rind, 1999; Shindell et al., 1999, 2001). However, caution is needed when considering the influence of solar variability on climate changes based on correlations between the records (Bard and Frank, 2006). Chronological controls are extremely important in spectral analysis, and in particular, we cannot determine past changes in the carbon reservoir age at Dagze Co, which would potentially cause significant deviation in spectral peaks.
Nevertheless, the close correlation and similarity of the spectral peaks between solar variability and temperature at Dagze Co implies the influence of solar variability on temperature changes on the TP.

Conclusion

Dagze Co provides the first quantitative temperature record and precipitation isotope record from the central TP. During the past 1000 years, the interval corresponding to the LIA was cool and dry and that corresponding to the MWP was warm and humid. These results suggest that during this interval, the climate was mainly influenced by the Indian summer monsoon. Precipitation isotope ratios tended to be lower between 2000 and 1000 cal. yr BP, implying a cool and humid climate and reflecting the influence of both the monsoon and the Westerlies. The temperature record exhibits a prominent 210-year cyclicity, which is also revealed in records of solar variability, implying a significant solar influence on temperature variability in the central TP.

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